River Research and Applications

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RESEARCH ARTICLE OPEN ACCESS

Evaluation of Human Impact on Sediment Dynamics in an Intensively Managed Agricultural Watershed Using Distributed Modeling

Mingjing Yu | Bruce L. Rhoads

Department of Geography and Geographic Information Science, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

Correspondence: Bruce L. Rhoads (brhoads@illinois.edu)

Received: 24 January 2025 | **Revised:** 27 April 2025 | **Accepted:** 28 April 2025

Funding: This work was supported by the National Science Foundation (Grant # EAR-1331906).

Keywords: agriculture | distributed modeling | human impact | rivers | sediment dynamics | watershed

ABSTRACT

By altering hydrological and geomorphological processes at watershed scales, humans have substantially influenced the movement of sediment on Earth's surface. Despite widespread recognition of human impacts on erosion and deposition, few studies have assessed the magnitude of change in watershed-scale sediment fluxes before and after the implementation of industrial agriculture and how agricultural development has altered the spatial distribution of sediment fluxes throughout watersheds. This study uses a modeling approach to explore changes in sediment fluxes before and after agricultural development in the upper Sangamon River Basin—an agricultural watershed in the midwestern United States. Comparison of model predictions with river hydrological and sediment data and with information on soil erosion and floodplain sedimentation shows the model accurately captures contemporary fluxes of water and sediment. To assess human impact, native land-cover conditions are used to estimate the magnitude and spatial distribution of sediment fluxes before the landscape was transformed by farming practices. Results suggest that sediment delivery from hillslopes to streams in this low relief watershed has increased 11-fold and the sediment load in streams has increased eight-fold since European settlement. Floodplain sedimentation has also increased dramatically, a finding consistent with recent estimates of post-settlement alluvium accumulation rates. The proportion of sediment exported from the basin is now slightly greater than it was in the 1800s. Overall, the model results indicate that humans have greatly enhanced the movement and storage of sediment within the upper Sangamon River basin.

1 | Introduction

Humans have become major geomorphological agents causing substantial change in the characteristics of Earth's physical landscapes (Hooke 1994; Wilkinson and McElroy 2007; Cooper et al. 2018). In the midwestern United States, the imprint of human agency is especially pervasive. Widespread conversion of native prairie to cropland and areas of grazing in the 19th century has produced an intensively managed landscape in which human reworking of the soil, enhancement of drainage, and modification of streams to support agricultural production are now integral components of landscape dynamics. In East Central Illinois, an estimated 15 million hectares of native prairie have been reduced to less than 10 ha (Rhoads and Herricks 1996). The hydrology of hillslopes has been modified by installing subsurface tiles (permeable pipes) to improve the drainage of relatively flat farm fields. Many headwater streams have been channelized and extended headward to provide outlets for the extensive tile-drainage systems (Urban and Rhoads 2003; Rhoads et al. 2016). Between 80% and 100% of the total length of headwater streams is now channelized in some areas (Mattingly et al. 1993). Through human modification, this landscape has been changed from primarily a transformation-dominated system characterized by long residence times and substantial storage of water, nutrients, and sediment to a transport-dominated system characterized by rapid movement and limited storage of water, nutrients, and sediment (Rhoads et al. 2016; Kumar et al. 2018, 2023).

A key issue of concern related to intensively managed agricultural landscapes of the Midwest is the influence of contemporary agricultural practices on the erosion, transport, and deposition of sediment. Many sustainable ecosystem services, such as soil productivity and water quality, on which human populations depend, are threatened by enhanced sediment fluxes. Whereas concern about loss of soil due to erosion of farmland has been well documented (Montgomery 2007; Nearing et al. 2017), the fate of eroded sediment as it moves off of hillslopes into stream systems has been less well documented. Excessive loads of sediment degrade water quality and transport nutrients, particularly phosphorus downstream, contributing to hypoxia in the Gulf of Mexico (Robertson and Saad 2021; Karimi and Obenour 2024). Locally, excessive sediment loads promote rapid sedimentation of water supply reservoirs and alter the carbon biogeochemistry of these reservoirs (Blair et al. 2018).

Undoubtedly, human-induced change in agricultural landscapes of the midwestern United States has altered sediment fluxes, but the magnitude and spatial variability of change in these fluxes remain unknown. Quantifying contemporary sediment fluxes in relation to pre-agricultural fluxes provides a benchmark for evaluating the extent to which humans have modified amounts and patterns of sediment movement at watershed scales. This type of knowledge is useful for the development of alternative land management practices aimed at mitigating human impacts (Gregory 2006). Unfortunately, modification of the landscape occurred prior to the collection of scientific information on the effects of this modification. Moreover, the degree of modification has been so profound and widespread that few, if any, undisturbed areas remain to provide a basis for comparison with disturbed areas (Rhoads and Herricks 1996). Over the past 20 years, computational modeling has become an effective tool for studying sediment supply, transport, and load in various environments (Papanicolaou et al. 2008; Patil et al. 2012; Papanicolaou and Abban 2016; Tsuruta et al. 2018, 2019). Models provide useful tools for evaluating changes in sediment dynamics caused by the transformation of landscapes from native vegetation to agriculture.

This paper addresses two fundamental research questions related to human influence on sediment fluxes in an intensively managed, low-relief agricultural watershed in the midwestern United States: (1) how has the transformation of a predominantly prairie landscape into a modern industrial agricultural landscape changed the magnitude of sediment fluxes and (2) how has this transformation influenced spatial variability of sediment fluxes, including source, storage, and export components of sediment dynamics? To address these questions, the study applies a semi-distributed, coupled hydrological and sediment flux model to explore contemporary sediment dynamics in an agricultural watershed in Illinois and to estimate how change in land cover in this landscape since the time of European settlement has altered sediment fluxes and storage. Sediment budgets provide an organizing framework for understanding sediment dynamics at the watershed scale (Reid and Dunne 2003). Existing sediment budgets for watersheds in the Midwest only include fluxes since the time of European settlement and agricultural production, rather than comparing these rates to estimates of rates under native vegetation cover (Trimble 1983, 1999, 2009; Beach 1994; Belmont et al. 2011). Moreover, these budgets have been developed for moderately to highly dissected watersheds, rather than for relatively undissected, low-relief glacial depositional landscapes that characterize much of the farmland in the upper Midwest. The results of this study inform the hypothesis that farming has enhanced material fluxes within watersheds of human-modified agricultural landscapes (Kumar et al. 2018).

2 | Study Area

The study area is the Upper Sangamon River Basin (USRB), Illinois, USA (Figure 1). Since the time of European settlement in the 19th century, the majority of the low-relief (< 50 m) landscape of the USRB has been converted from prairie and scattered forest to agriculture (Rhoads et al. 2016). Land cover consists mainly of agricultural lands dominated by row-crop agriculture (≈90% of total land use). Localized areas of grazing occur at a few locations along headwater tributaries. Forest exists along a riparian corridor flanking the middle and downstream portions of the main river. A few small agricultural communities are scattered throughout the watershed. Areas of highest relief occur in headward portions of the watershed and along the main river, which has incised about 10–15 m, forming a broad valley bottom bounded by adjacent bluffs. Soils have developed in surficial loess deposits, which are underlain by glacial sediments deposited by the Lake Michigan Lobe of the Laurentide Ice Sheet during the Wisconsin Glacial Episode (Kumar et al. 2018).

To provide outlets for subsurface tiles, many headwater channels throughout this region have been channelized, or straightened, deepened, and widened (Rhoads and Herricks 1996; Urban and Rhoads 2003). Many channelized portions of streams show little or no evidence of recovery to human modification. Historical analysis of channel change indicates that the modern channel network is nearly three times more extensive than the channel network in the 1820s (Rhoads et al. 2016, Figure 3). Expansion of the network occurred through the construction of drainage ditches on flat, poorly drained uplands.

The meandering Sangamon River exhibits remarkable lateral stability with little or no movement of the channel over a period of 70–80 years. Except for a few localized areas along tributaries and in the headwaters of the Sangamon River, rates of lateral migration are less than 1–2 channel widths over a period of more than 70 years (Rhoads et al. 2016). Reconstruction of meander migration over the last ≈1500 years indicates that rates of lateral movement have been on the order of 0.15 m/year over this period (Rhoads et al. 2024). Many meandering reaches of the Sangamon River and its tributaries have been artificially straightened, yet remain stable in this configuration. No evidence exists of major channel incision along tributaries or the main stem. Headwater tributaries are artificially incised through the construction of drainage ditches. Many ditches are overly wide and therefore

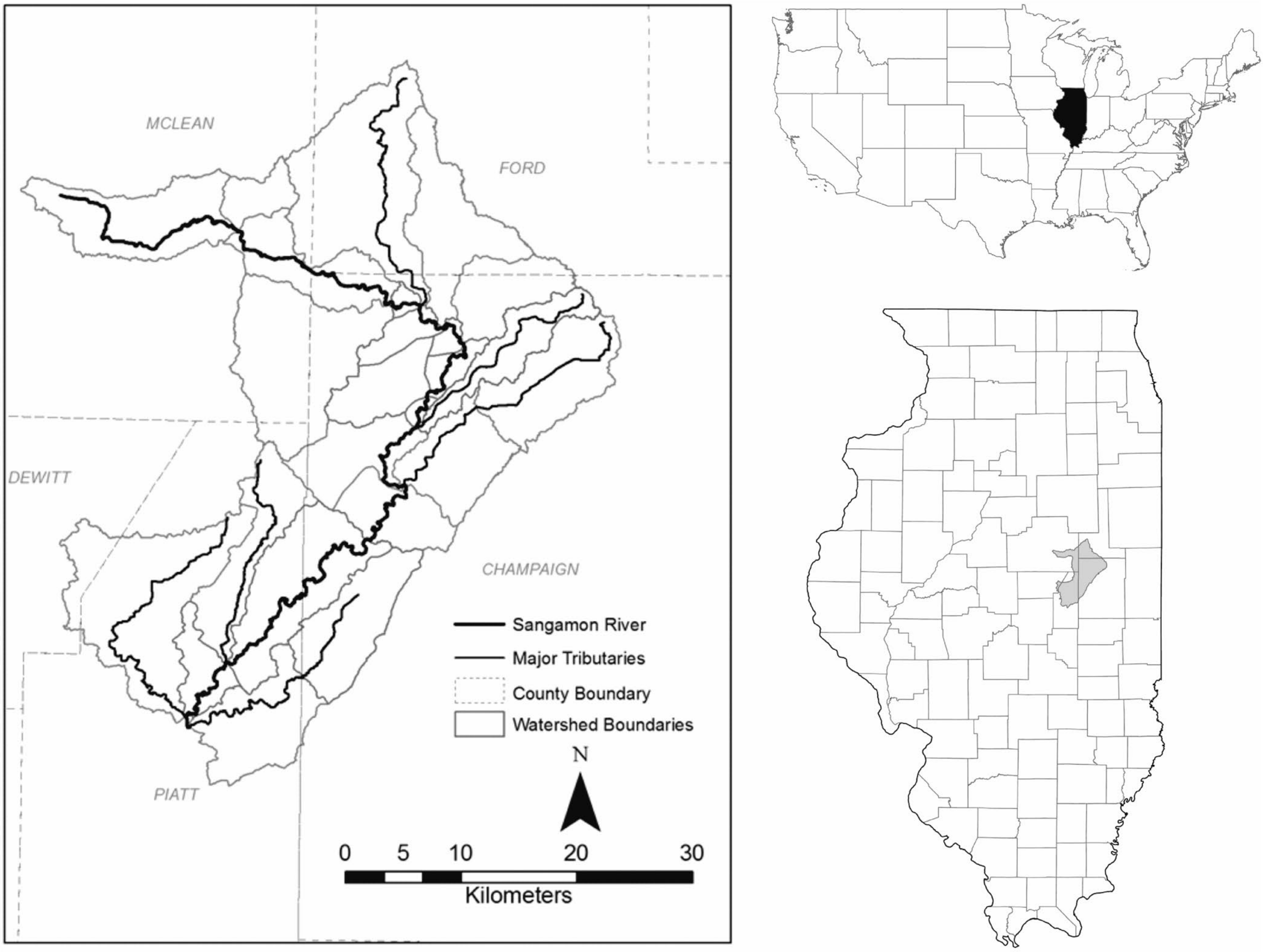

FIGURE 1 | The Upper Sangamon River Basin upstream of the gaging station at Monticello, IL with Representative Elementary Watershed delineation used in the model.

prone to accumulation of sediment on ditch bottoms (Landwehr and Rhoads 2003).

3 | Integrated Water-Sediment Modeling Framework

The modeling framework adopted for this study combines a network hydrology model based on the representative elementary watershed (REW) theory (Reggiani et al. 2001) with a network sediment-transport model (Viney and Sivapalan 1999) within the context of a large scale catchment model (LASCAM) (Sivapalan et al. 2004). Only key processes are described here for the sake of brevity. Quantitative details of hydrological and sediment-transport relations constituting the model can be found in Tian et al. (2008), Li et al. (2010), Patil et al. (2012), and Ye et al. (2012). The network sediment-transport model captures sediment delivery from hillslopes to streams and sediment propagation through streams (Patil et al. 2012) and the integrated hydrology-sediment modeling framework has been used successfully in other studies to model sediment dynamics at the watershed scale (Patil et al. 2012; Liu et al. 2019). The semi-distributed framework operates at a fine temporal scale (sub-daily) and can also be applied at the spatial scale of coarse models (> 1000 km^2) (Li et al. 2010; Patil et al. 2012; Ye et al. 2012; Tsuruta et al. 2018, 2019; Liu et al. 2019). It is also capable of continuously simulating watershed dynamics over long periods (multiple years) with reasonable computational expenditure.

3.1 | Representative Elementary Watershed (REW) Theory

The modeling framework is based on the TsingHua Representative Elementary Watershed (THREW) model (Tian et al. 2008) of hillslope runoff and stream flow that incorporates balance equations for mass and momentum for a hierarchical river network. The framework represents a watershed as a set of representative elementary watersheds (REWs), which constitute the smallest functional units of the model (Figure 2). Each REW consists of hillslope and channel components (Reggiani et al. 1998) and REWs connect through the river network (Ye et al. 2012; Patil et al. 2012). The hillslope component comprises a surface layer and a sub-surface layer (Tian et al. 2008). Surface layers are classified as bare soil (b-zone),

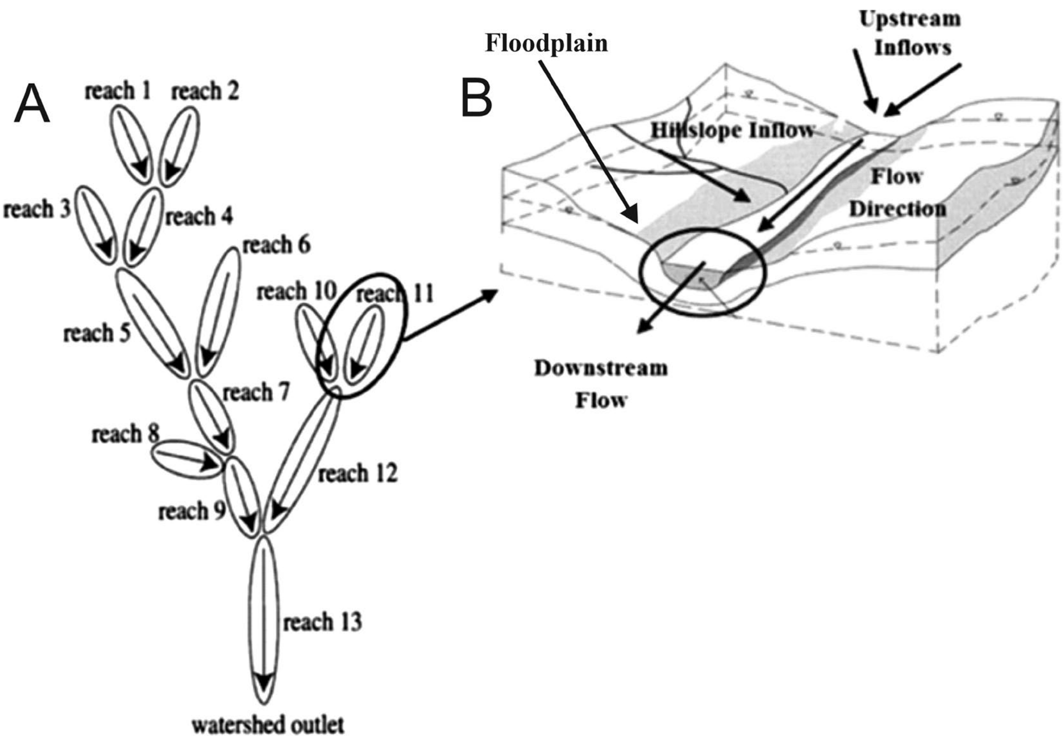

FIGURE 2 | Schematic of the coupled hydrological-solute-transport model: (a) Watershed discretization into several REWs organized around the river network; and (b) each REW includes a hillslope and a channel reach (modified from Ye et al. 2012).

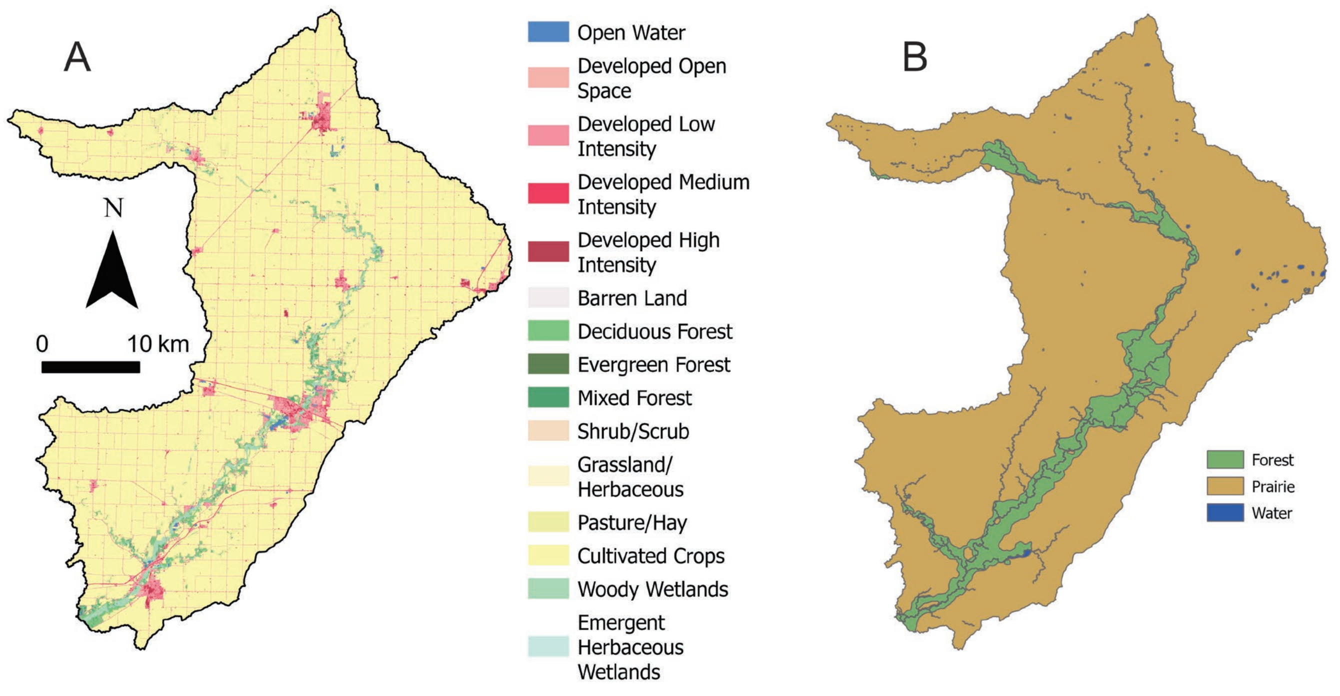

FIGURE 3 | Land cover in the USRB upstream of Monticello: (a) 2000s land cover obtained from the National Land Cover Database 2011. (b)1840s land cover retrieved from the Illinois Geospatial Data Clearinghouse. [Color figure can be viewed at wileyonlinelibrary.com]

vegetated areas (v-zone), and sub-stream-network zone (t-zone). Subsurface layers are categorized as saturated (s-zone) and unsaturated (u-zone) zones. Water is exchanged between surface and subsurface zones. Every stream reach receives water from upstream REWs and adjacent hillslopes. Sediment inputs come from upstream REWs and from erosion of adjacent hillslopes and the channel bed (Patil et al. 2012). An existing version of the modeling framework (Patil et al. 2012) was modified to include floodplain elements (besides channels and hillslopes) and to simulate floodplain sedimentation. Floodplains, as defined in this study, are depositional features that flank the main channel and occur adjacent to the tops of the channel banks (Lindroth et al. 2020).

3.2 | Network Hydrology Model

3.2.1 | Hillslope Hydrological Processes

Hillslope hydrological processes in the model include ground-surface depression storage, canopy interception, saturation and infiltration excess runoff, and routing of overland and channel flow. A set of ordinary differential equations accounts for conservation of mass, momentum, and energy (Tian et al. 2008). Surface runoff contributed from the hillslopes to channels consists of infiltration excess runoff from the bare soil zone (b-zone) and the vegetated zone (v-zone), saturation excess runoff from the sub-stream-network zone (t-zone), and baseflow from the saturation zone (s-zone) (see Tian et al. 2008, Figure 1). Infiltration rates in the unsaturated subsurface zone (u-zone) are influenced by rainfall intensity and infiltration capacity. In the model, infiltration capacity is characterized by the Green-Ampt model (Rogers 1992). The t-zone includes the saturated area of land surface and water bodies other than the main channel, which together can be regarded as a variable contributing area. The area of the t-zone is calculated using the Xin'anjiang model (Zhao 1992). Baseflow, water flowing from the s-zone to the channel, is determined based on the spatially averaged saturated hydraulic conductivity of this zone.

3.2.2 | River Hydrological Processes

River hydrological processes are modeled based on water balance equations for the channel and floodplain flow (r-zone) in each REW, accounting for inflows from the hillslope and upstream REWs. The cross-sectional area of the flow at the beginning of any time step is estimated by dividing the water storage at the end of the previous time step by the r-zone length. When water depth exceeds the channel depth, overbank flow and floodplain inundation occur. The water storage in the reach is then re-distributed between the main channel and floodplain. Velocities in the river channel and on the floodplain are estimated using a simplified reach-scale Saint-Venant momentum balance equation (Reggiani et al. 2001; Ye et al. 2012; Patil et al. 2012). Floodplain velocities (u_f) are estimated using the same relation for channel velocities (u_c) but, given the heavily forested nature of the floodplain along the Sangamon River and its tributaries, with a five-fold increase in flow resistance. Outflow from the REW is the summation of water flow from the channel and floodplain, which is the inflow to the downstream reach.

3.3 | Network Sediment Transport Model

The sediment component of the modeling framework simulates the sediment transport process in a watershed in three stages: sediment generation from hillslopes, sediment propagation through the river channel network, and sediment deposition on floodplains. The model simulates the behaviors of sand and mud transport processes separately and assumes all sediment transported in the streams is in suspension.

3.3.1 | Hillslope Sediment Processes

Sediment is generated on hillslopes and transported into river channels by surface runoff. The sediment erosion rate on hillslopes is a generalized formulation of the Universal Soil Loss Equation (USLE) (Viney and Sivapalan 1999). This generalized formulation allows hillslope sediment delivery to channels to be calibrated to data on stream sediment loads by varying the value of the cover management factor (C) while accounting for the effects of modeled in-channel fluxes of sediment. The model thus avoids the need to consider sediment delivery ratios in the prediction of fluxes of sediment from hillslopes into channels.

3.3.2 | Channel Sediment Processes

Modeling of deposition and entrainment in channels follows the conceptual model of water and sediment fluxes developed from the LASCAM model (Viney and Sivapalan 1999). Sediment entrainment in the channel is a function of stream carrying capacity and critical shear stress. Sediment transport capacity [maximum concentration, C_s (kg/m^3)] is related to stream velocity as a power function: $C_s = 0.01 u_i^{1.5}$ where u_i is equal to u_f or u_c (Williams 1980; Arnold et al. 1995; Neitsch et al. 2009). The calculated sediment transport capacity is compared to the actual sediment load transported in the reach. If the actual sediment load is greater than the sediment transport capacity, deposition occurs. If the sediment load in the stream is smaller than the transport capacity and the bed shear stress is larger than the critical shear stress, erosion will occur. Erosion rate increases in proportion to the extent to which the actual shear stress exceeds the critical shear stress (Patil et al. 2012).

3.3.3 | Floodplain Sediment Processes

The basic modeling framework (Patil et al. 2012) was expanded in this study to consider floodplain deposition, an important factor in watershed-scale sediment dynamics, by including a one-dimensional floodplain sedimentation component in the model. When a floodplain is inundated, water and sediment enter the floodplain at the upstream end of the REW. Part of the sediment transported by the flow is deposited, and flow with a reduced sediment load leaves the floodplain at the downstream end of the REW. The modeling approach of floodplain sedimentation is based on the procedure (Chen 1975) developed to estimate sedimentation in settling tanks as a function of the trapping efficiency of the tank (Asselman and van Wijngaarden 2002). The floodplain trapping efficiency (TE) in each REW is calculated as:

$$TE = 1 - \exp\left(-v_f \frac{A_f}{Q}\right) \tag{1}$$

where v_f is the settling velocity of the suspended sediment (m/s), A_f is the surface area of the floodplain (m^2), and Q is the discharge (m^3/s). This efficiency is a function of the ratio between floodplain area and the discharge through it (Asselman and van Wijngaarden 2002), which reflects the residence time of water and sediment in the floodplain. The sedimentation rate is computed as:

$$S = Q_s \times TE \tag{2}$$

where S is the sedimentation rate (kg/s) and Q_s is the suspended sediment load (kg/s). An assumption of this formulation is that advection rather than diffusion (e.g., Pizzuto 1987) causes sedimentation (Chen 1975; Asselman and van Wijngaarden 2002). Another assumption is that no re-suspension or erosion occurs on the floodplain regardless of bed shear stress or potential sediment sources on the floodplain (Asselman and van Wijngaarden 2002). Thus, floodplains are sinks for transported sediment.

4 | Model Application—Scenarios and Input Data

This study uses the modified modeling framework to simulate sediment generation, transport, and loads for the Upper Sangamon River Basin upstream of a US Geological Survey stream gauging site at Monticello, IL. Two different scenarios are examined. The first scenario, referred to as the 2000s scenario, represents the water and sediment fluxes within the modern agricultural landscape. The second scenario, referred to as the 1840s scenario, represents landscape conditions before European settlement. The model was first calibrated for a two-year period (1 October 1995 to 30 September 1997) to best match observed records of water discharge and sediment load. The calibrated model was validated by applying it to a 10-year period (1 October 1995 to 30 September 2005) for the 2000s scenario. It was then used to simulate sediment fluxes for the 1840s scenario based on land cover and stream-channel conditions that existed at that time. Modeling results of the two scenarios were then compared to provide insight into human impacts on watershed-scale sediment dynamics.

For computational efficiency, the Upper Sangamon River Basin upstream of the Monticello gage site was divided into 21 REWs (Figure 1), which is appropriate based on previous REW modeling for this landscape (Li et al. 2010). The Nash-Sutcliffe coefficient (Nash and Sutcliffe 1970) was used to evaluate the parameters required to produce a best fit over the calibration period and to evaluate model performance for the 10-year model-assessment period corresponding to the 2000s scenario. This coefficient measures the goodness of fit in relation to a line of perfect fit (the 1:1 line), indicating how well simulated and observed data correspond. The coefficient can range from $-\infty$ to 1, with a value of 1 equivalent to exact agreement between predicted and observed data.

Model inputs include data on precipitation, temperature, land cover, soil order, and watershed characteristics. The precipitation and temperature conditions for the two scenarios are assumed to be identical. Although temperature and precipitation have been altered at a global scale by human activities, this factor is not considered in this study; the same temperature and precipitation data are used for the two scenarios to evaluate the response of the watershed to differing landscape conditions. Hourly precipitation data at Champaign, Illinois, were obtained from the National Climatic Data Center (NCDC) of NOAA. Data on soil characteristics were extracted from the STATSGO database.

Land cover data for the 2000s scenario were obtained from the National Land Cover Database 2011 (Figure 3). Digital maps produced by the Illinois Natural History Survey from original General Land Office (GLO) survey maps provided land cover data for the 1840s scenario; these maps are available through the Illinois Geospatial Data Clearinghouse (https://clearinghouse.isgs.illinois.edu/data/landcover/illinois-landcover-early-1800s) (Figure 3). The cover management factor (C) in the model is an important variable for comparing sediment fluxes between the two scenarios. This factor is related to vegetation/crop type. The land cover maps for the two scenarios (Figure 3) were used to generate appropriate C values for each REW weighted by the spatial distributions of different cover types.

Watershed characteristics such as drainage area and average gradients of hillslopes were extracted from DEM data available through the Illinois State Geological Survey with a spatial resolution of 30 m; channel length, channel top width, and floodplain width were extracted from airborne LiDAR with a resolution of 1.2 m. Historical channel length and width were measured from maps of the stream network in the USRB produced from General Land Office (GLO) surveys (Rhoads et al. 2016). Floodplain width, watershed slope, drainage area, and soil order inputs for the 1840s scenario are assumed to be the same as those for the 2000s scenario.

Calibration and model-assessment data for the 2000s scenario included USGS records of streamflow for the Sangamon River at Monticello, IL, and suspended sediment records for the same station collected as part of the Illinois State Water Survey Sediment Benchmark monitoring program (Allgire and Demissie 1995). Annual sediment loads at Monticello were estimated from a sediment-rating curve developed for this station (Figure 4). The model is calibrated only to data on suspended sediment loads because no bedload data are available for the Sangamon River and because bedload is typically not a major fraction (< 2%) of the total annual sediment load in rivers of Illinois (Bhowmik et al. 1980). Most (> 90%) sediment transported by the Sangamon River consists of fine sand, silt, and clay (Blair et al. 2018). The transport of two sizes of material, sand (≥ 0.0625 mm) and mud (< 0.0625 mm),

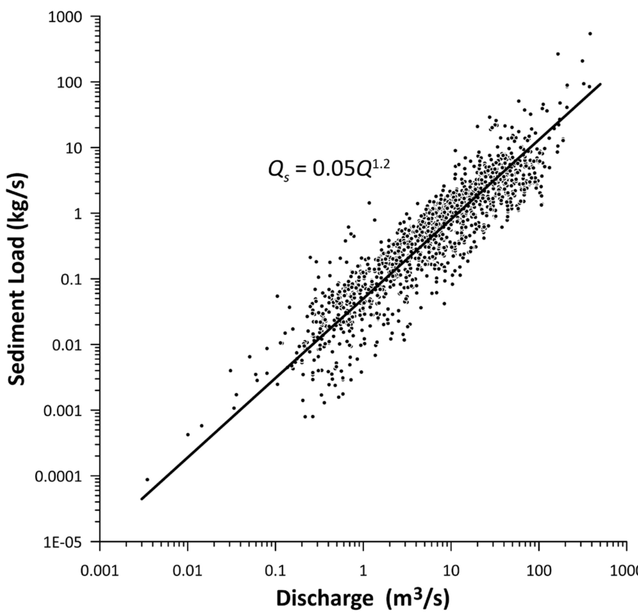

FIGURE 4 | Suspended sediment rating curve for the Sangamon River at Monticello.

are treated separately in the model (Patil et al. 2012). It is assumed that mud supply comes from hillslope erosion and that no mud fraction is deposited within the channel system, but that mud can be deposited on floodplains. Deposition of sand can occur both within the channel system and on floodplains. The sand fraction of sediment eroded from hillslopes is assumed to be 10% -a reasonable value given the fine-grained nature of the silt-loam and silty-clay-loam soils in the watershed, which contain 0%–30% sand (Natural Resources Conservation Service 2010), and the lower mobility of sand relative to silt and clay.

In the model, sediment entrainment, deposition, and transport processes are directly related to the depth and width of stream reaches in each REW. Spatial variations in width and depth influence flow geometry, which in turn affects the bed shear stress and sediment transport capacity. Empirical channel geometry relations for the Sangamon River basin are (Stall and Fok 1968):

$$w = 2.5A^{0.43}{A_d}^{0.18} \tag{3}$$

$$d = A/w \tag{4}$$

where w is the channel top width (ft), d is bankfull channel depth (ft), A is channel cross-sectional area (ft^2) and A_d is the drainage area (mi^2). These relations, with w and d converted to meters, were used to characterize channel geometry across the Upper Sangamon River Basin in the 2000s scenario.

Channel widths reported in General Land Office (GLO) survey notes reveal that contemporary widths of the Sangamon River are slightly less than those of the pre-settlement river channel, whereas headwater channels today are wider than those in the pre-settlement drainage network. The relationship between 1840 and modern channel widths can be expressed as:

$$w_{2000} = 6.0{w_{1840}}^{0.43} \tag{5}$$

where w_{2000} and w_{1840} are channel widths (m) in the 2000s and 1840s, respectively. Moreover, the relationship between channel width and drainage area (A_d, km^2) for the 1840s is:

$$w_{1840} = 2.0{A_d}^{0.79} \tag{6}$$

Equations (5) and (6) were used to characterize pre-settlement channel widths by averaging the results of the two methods.

Characteristics of artificial levees along drainage ditches and channelized headwater streams were determined from airborne LiDAR data. Ten to twenty stream cross-sections derived from the LiDAR data were averaged to define the heights of levees along drainage ditches and channelized streams. In the 2000s scenario, the level of floodplain inundation is the sum of channel depths and levee heights. No artificial levees were included in the 1840s scenario; thus, the depths of channels in this scenario are natural channel depths.

5 | Model Calibration

The integrated model was first calibrated for a two-year period (October 1995—September 1997). Values of inputs for each REW for several hydrological variables, including hydraulic conductivity, soil porosity, field capacity, air entry value, soil pore size distribution index, and ground surface depression capacity were derived from soil-survey data in the watershed or were specified based on previous applications of the model in East Central Illinois (Ye et al. 2012), including the upper Sangamon River basin (Li et al. 2010). An automated parameter optimization procedure was not performed; instead, a few key parameters were varied to calibrate the model. Hydrological parameters included coefficients governing baseflow discharge, and sediment parameters included parameters governing the hillslope erosion rate and the suspended-sediment transport capacity. Model performance was evaluated by comparing observed and simulated data using the Sutcliffe-Nash coefficient. The calibrated model has Nash-Sutcliffe coefficients for predicted daily water discharge and suspended sediment load for the calibration period (1 October 1995 to 30 September 1997) of 0.70 and 0.68, respectively, indicating that the model captured reasonably well the variability in water discharge and suspended sediment fluxes.

6 | Assessment of Model Performance

The calibrated model was applied to simulate daily water and sediment loads for the 2000s scenario from October 1995, to September 2005. The model predicts accurately mean monthly discharges during the 10-year period (Figure 5). Slight underestimation of discharges in early spring may be related to snowmelt, which was not included in the model.

The model predicts accurately the pattern of variation in mean monthly sediment loads over the 10-year model-assessment period (Figure 6). The Nash-Sutcliffe coefficient for observed versus predicted sediment loads is 0.91, suggesting the model captures well seasonal variability in mean monthly sediment loads. As expected, this pattern of variability mirrors closely variability in the pattern of discharge (Figure 6) given the strong dependence of sediment load on discharge. The highest mean monthly sediment loads occur in February and May, when runoff is high and soil in the watershed is fallow or newly planted. Sediment loads are lowest in September and October, a relatively dry period of the year when mature crops cover vast portions of the watershed.

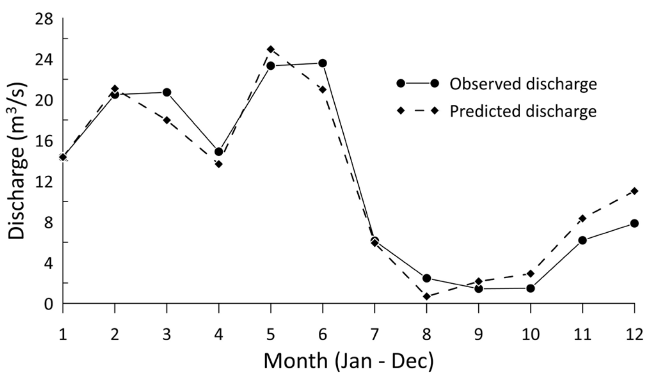

FIGURE 5 | Observed and predicted mean monthly discharges over 10 years.

7 | Difference in Sediment Dynamics Between Pre-Settlement and Modern Conditions

The model predicts that all fluxes—delivery, storage, and export—were much less in the 1840s for the exact same weather conditions corresponding to the 2000s scenario (Figure 7). Sediment delivery to the streams from hillslope erosion since the 1840s has increased approximately 11-fold, reflecting the enormous influence of change in land cover from prairie to row-crop agriculture on soil erodibility. The annual sediment load of the Sangamon River in the 2000s at the outlet of the watershed is eight times greater than the estimated load in the 1840s. The estimate of floodplain sedimentation is 6.5 times greater today than in the 1840s, whereas in-channel sediment deposition is predicted to have increased by a factor of 30. The only aspect of the sediment budget that is estimated to have been greater in the 1840s than today is channel erosion, which today constitutes about 63% of the 1840s value. The increase in stored sediment within the water column throughout the network during the simulations is similar for the two scenarios, with the 2000s value differing by only 8% from the 1840s value.

When considering the distribution of fluxes as percentages of the total sediment flux within the watershed, sediment supply from hillslopes increased from 60% to 96% from the 1840s to 2000s (Figure 8), indicating that hillslope erosion now dominates delivery of sediment to streams. In the 1840s, erosion of channels constituted about 31% of the total sediment supply, but today this source represents only 3% of the supply. This change mainly reflects the enormous increase in hillslope supply, which now dwarfs channel erosion. Despite the large increase in total floodplain sedimentation between 1840 and today, the percentage of sediment deposited on the floodplain has decreased slightly from 50% to 44%. On the other hand, slightly higher percentages of sediment are transported out of the system and deposited within channels in the 2000s than in the 1840s. Although the percentage of delivered sediment

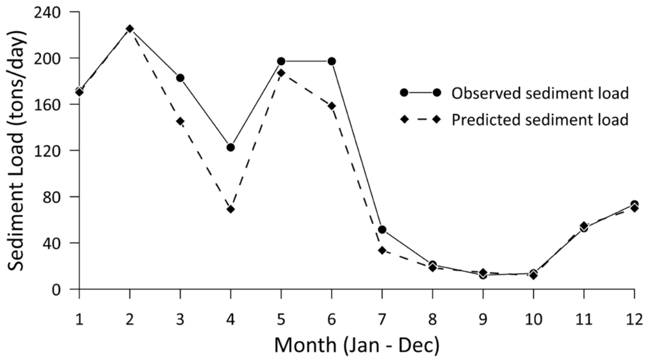

FIGURE 6 | Observed and predicted mean monthly sediment loads over 10 years.

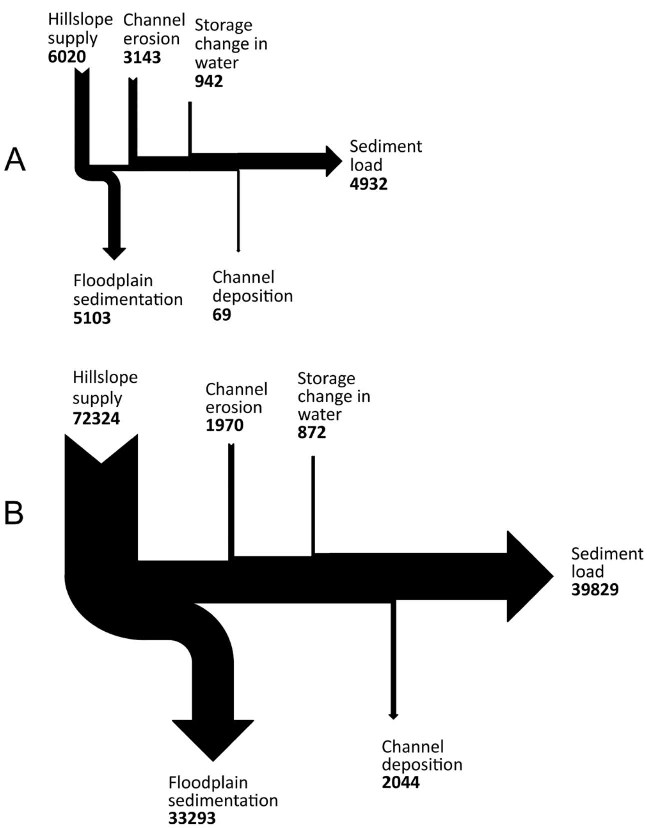

FIGURE 7 | Estimated sediment fluxes in tons (Mg)/year for (A) 1840s and (B) 2000s.

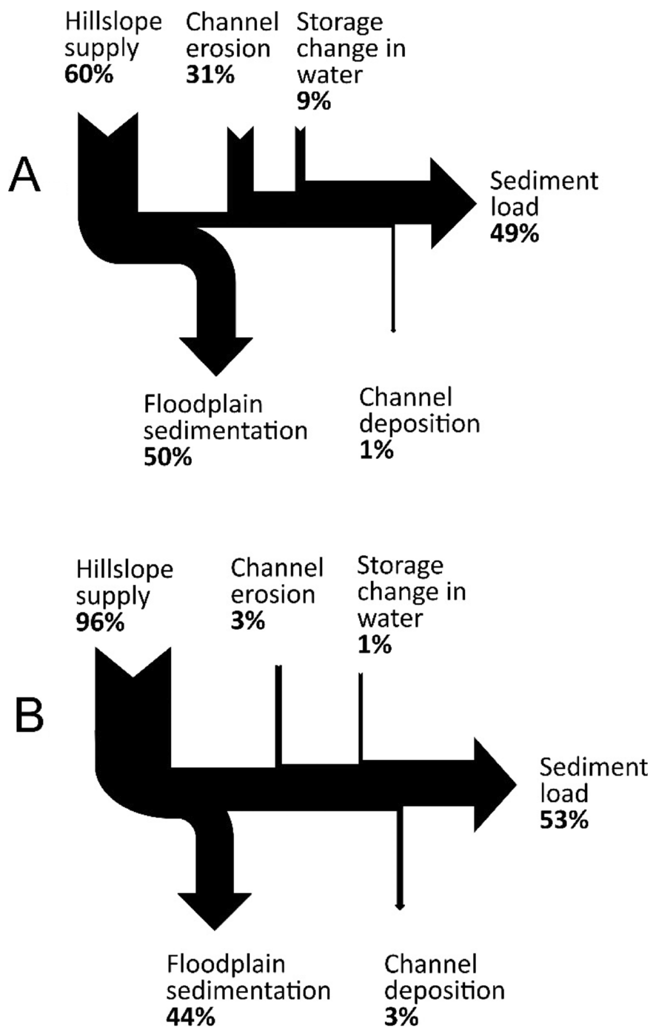

FIGURE 8 | Percent of sediment sinks and load for (A) 1840s and (B) 2000s.

TABLE 1 | Floodplain sedimentation rates estimated by the model and through using fly ash.

	Time period	Tributaries (mm/year)	Mainstem (mm/year)
Grimley et al. 2017	Pre-settlement	0.09	0.70
	1960–2015 CE	2.00	6.00
Model estimation	1840s	0.06	0.22
	2000s	0.58	1.19

has shifted largely to hillslope-derived material, the percentage distribution of sediment deposited in sinks and exported from the basin today is not dramatically different from the distribution in the 1840s. Despite enormous changes in fluxes of sediment within the watershed, the percentage of sediment delivered to streams that leaves the watershed has increased only slightly because increased mobility has nearly been balanced by increased storage.

The sediment delivery ratio (SDR), which is the ratio of sediment load of a watershed to the total amount of soil detachment (Walling 1983; Abaci and Papanicolaou 2009), is often used to relate sediment load to gross erosion rates (Lu et al. 2005). SDRs calculated for the entire watershed for the 1840s and 2000s are 49% and 53%, respectively. Because the model estimates sediment supply from hillslopes to streams in a lumped fashion and does not account for erosion, transport, and redeposition of sediment on hillslopes, SDRs as calculated in this study represent the ratio of sediment yield to sediment delivery to the stream network, rather than the total amount of soil erosion. These values of SDR reflect the efficiency by which streams transport sediment delivered to them by hillslope or channel erosion to the watershed outlet (Rhoads 2020). Because the redeposition of eroded soil on hillslopes is not accounted for by the model, SDR values in the present study are greater than SDR estimates that account for redeposition, which range from less than 10% to about 35% for watersheds in the midwestern United States (Trimble 1983; Beach 1994). In this flat landscape, the transport of sediment from hillslopes to streams is not expected to be efficient. The delivery ratios of suspended sediment load to detached sediment within the watershed, the typical way in which the SDR is expressed, undoubtedly are much lower than the SDRs estimated by the model. When budgets from past studies are expressed in terms of net hillslope erosion, the SDR values increase to 30%–60% (Beach 1994; Trimble 2009), results consistent with those in the present study.

Floodplain sedimentation rates in the 2000s are a magnitude higher than those in the 1840s, which is consistent with the average alluvial sediment rates in the USRB estimated by Grimley et al. (2017) using fly ash dating of floodplain sediments (Table 1). Floodplain sedimentation rates are estimated to have increased from 0.06 to 0.58 mm/year in tributaries and from 0.22 to 1.19 mm/year in the Sangamon River. Tributaries have lower floodplain sedimentation rates than the mainstem in both scenarios. The model predicts somewhat lower floodplain sedimentation rates than those estimated by Grimley et al. (2017). Materials deposited on the floodplain are assumed to be evenly distributed across the entire floodplain in the model, whereas the floodplain sedimentation rates estimated through using fly ash were based on measurements at 17 sample sites. Considerable variability in floodplain sediment concentrations and sedimentation rates exists among different locations on the floodplain of the Sangamon River (Arnott 2015; Salas and Rhoads 2022). Spatial heterogeneity of floodplain sedimentation rates might explain differences between local estimates of floodplain sedimentation rates by Grimley et al. (2017) and general floodplain sedimentation rates estimated by the model.

8 | Discussion

The semi-distributed, coupled hydrologic and sediment model developed in this study yields accurate estimates of modern water and sediment fluxes across multiple scales in the Upper Sangamon River basin—an intensively managed agricultural watershed in East Central Illinois. This outcome implies that the validated model should provide reasonable estimates of water and sediment fluxes within this watershed for the same weather conditions prior to the implementation of agriculture. Results of the simulations suggest that conversion of prairie to farmland has greatly increased sediment loads and sediment storage within stream systems of intensively managed agricultural landscapes of the Midwest. Relatively flat, low-relief agricultural uplands now introduce large amounts of suspended sediment into streams. The model estimates that sediment supply from uplands increased 11-fold from the 1840s to 2000s. Estimates of presettlement hillslope fluxes to streams in the present study (0.04 Mg/ha/year) are consistent with presettlement estimates of soil erosion rates in loess-covered low-relief landscapes in the midwestern United States (0.035–0.06 Mg/ha/year) (Norton 1986; Nearing et al. 2017). Estimates of modern hillslope fluxes (0.48 Mg/ha/year) are relatively low compared to contemporary soil-erosion rates for cultivated cropland, which have been reported as 6–9 Mg/ha/year (Nearing et al. 2017), but the model estimates seem reasonable for the low-relief (average slope < 1%) landscape of central Illinois. Estimated rates of soil erosion throughout the Midwest over the historical period of modern agriculture (≈150 years), including time prior to widespread implementation of soil conservation practices that have reduced overall soil erosion rates (Abaci and Papanicolaou 2009; Papanicolaou et al. 2015), exhibit a broad range of values (≈2 to 95 Mg/ha/year) and a measurement location near Loda, IL in a landscape similar to that of the Sangamon River has a median historical rate of about 10 Mg/ha/year (Thaler et al. 2022). The model-estimated hillslope fluxes in the present study do not account for redeposition of eroded soil on hillslopes (e.g., Blair et al. 2022) and therefore do not correspond directly to soil-erosion rates, which should be higher than rates of sediment delivery to streams from hillslopes. Wind erosion, not considered in this study, may also lead to disparities between actual and estimated erosion rates (Skidmore 1994). In any case, the comparison with published values suggests the model provides conservative estimates of modern sediment-flux delivery to streams from hillslopes. The predicted increase in hillslope fluxes from presettlement to the modern agricultural condition also conforms to results of experimental research on soil erosion rates in native grassland versus cropped land, which show that erosion rates range from eight times greater for cropland with no-till to as much as 170 times greater for cropland with conventional tillage (Zhang and Garbrecht 2002).

With the transformation from prairie and forests to row crop agriculture, the annual sediment load of the Sangamon River in the 2000s is estimated to be eight times greater than the load in the 1840s. This dramatic increase in sediment load has important implications for water quality, river and stream habitat, fluvial dynamics, and human water-resources infrastructure. As a result of enhanced sediment fluxes of fine sediment in the Sangamon River, Lake Decatur, located 30 km downstream from Monticello, has rapidly filled with sediment. Between the damming of the river in the 1920s and the early 2000s, this 12 km^2 water-supply reservoir for the city of Decatur, IL lost more than one-third of its original volume (Fitzpatrick et al. 1987; Bogner 2002), necessitating the dredging of the lake between the mid-1990s and 2018s. This dredging removed 8.2 million cubic meters of sediment from the lake at a cost of $92 million dollars (Economic Development Corporation of Decatur and Macon County 2025). Today, large amounts of sediment continue to enter the lake.

The modeling results are consistent with the results of other sediment budget and modeling studies that suggest agricultural land use and associated management practices strongly influence the magnitude of soil erosion rates and increase stream sediment loads far above natural background levels (Meade and Trimble 1974; Montgomery 2007; Abaci and Papanicolaou 2009; Gran et al. 2013; Maalim et al. 2013). Sediment budgeting studies in the midwestern United States have largely focused on the magnitude of sediment fluxes associated with agricultural activity and the response of those fluxes to agricultural conservation practices without considering the magnitude of pre-settlement fluxes (Trimble 1983, 2009; Beach 1994). An exception is work in the Le Sueur basin in Minnesota where modeling suggests that transformation of land surface, vegetation, and hydrology since European settlement has increased sediment load by a factor of four to five (Gran et al. 2009, 2011; Maalim et al. 2013). The results of this study therefore contribute to the understanding of the extent to which the transformation of landscapes by industrial agriculture has accelerated fluxes of sediment delivery, storage, and transport within river networks.

The nearly seven-fold increase in floodplain sedimentation estimated by the model also is consistent with the results of other studies that have examined rates of sediment accumulation pre- and post-settlement (James and Lecce 2013); however, total thicknesses of accumulation are not as pronounced as in older glaciated or non-glaciated terrains in the Midwest with higher relief than the Sangamon basin, such as the Driftless Region of Wisconsin (Knox 1987, 2006; Magilligan 1992, 1985; Lecce 1997) and northeastern Iowa (Baker et al. 1993).

Despite the dramatic increases in total sediment flux, the estimated sediment delivery ratio for the entire watershed increased from only 49% to 53% from the 1840s to the 2000s. The percentage of floodplain sedimentation and channel deposition only changed 2%–6%, indicating that the increased sediment supply does not have a substantial impact on the fate of mobilized sediment. The results agree with the general conclusion of other work that the majority of eroded material remains trapped in watersheds (Haggett 1961; Walling 1983; Trimble 1999; Trimble and Crosson 2000; Wilkinson and McElroy 2007; Walter and Merritts 2008; Reusser et al. 2015). Annual channel deposition under present conditions is 30 times that under pre-settlement conditions—a result consistent with the three-fold increase in the density of headwater streams in the watershed and the persistent accumulation of sediment in headwater channels (Rhoads et al. 2016). Net deposition is a common fluvial response to stream channelization in agricultural drainage ditches, which motivates frequent excavation to remove accumulated sediment (Landwehr and Rhoads 2003).

The results of this study are constrained by several possible limitations. First, the approach of calibrating sediment delivery to streams based on sediment load data, while considering erosion and deposition on the bed of stream channels, assumes that this method effectively accounts for the net removal of sediment from hillslopes. No data are available from the watershed to determine the extent to which the model accurately estimates inputs of sediment from hillslopes to rivers, but the rates of soil loss predicted by the model are consistent with estimates of soil erosion rates based on the net loss of sediment from intensively farmed landscapes. The basic approach adopted here could be refined to fully account for hillslope processes by linking the stream-channel modeling components to other models, such as the Watershed Erosion Prediction Project (WEPP) model (National Soil Erosion Research Lab 1995) or various modifications of WEPP (Renschler 2003; Gelder et al. 2018; Papanicolaou et al. 2018; Luquin et al. 2024) that explicitly account for soil detachment, movement, and redeposition of sediment on hillslopes; however, without data on sediment fluxes from hillslopes to channels, model calibration and testing is not feasible. Recent work indicates that large amounts of eroded sediment in the USRB are redeposited on hillslopes rather than being delivered to streams (Blair et al. 2022). Redeposition of eroded sediment on hillslopes is likely to reduce sediment delivery to channels to a greater extent for native prairie than for contemporary agricultural land use so that percentage differences between pre-settlement and post-settlement sediment fluxes to rivers are probably underestimated. Second, the model does not include a streambank erosion component, and as noted by Patil et al. (2012), it could be improved by incorporating a lateral-migration and bank erosion module. Although erosion of streambanks has been shown to be a major source of sediment in some areas of the Midwest (Gran et al. 2009), widespread erosion of streambanks by lateral migration of channels does not occur in the Sangamon River basin over a timescale of many decades (Rhoads et al. 2016, 2024). It is even more limited over the modeling timescale of 10 years in the present study. Moreover, erosion of streambanks is largely balanced by deposition within channels on point bars, as indicated by the lack of enlargement of channels over time (Rhoads et al. 2024), especially over a period of 10 years. Recent tracing of fine sediment in the headwaters of the USRB suggests that active lateral migration of the Sangamon River channel along with erosion of the floodplain by surface runoff in areas of intensive cattle grazing locally contributes the majority of fine sediment to the instream load (Yu and Rhoads 2018). However, related work using different tracers suggests that upland sources of sediment may be more important than indicated by Yu and Rhoads (2018). At the watershed scale, the biogeochemical characteristics of accumulated sediment within Lake Decatur, an artificial water-supply reservoir into which the Sangamon River flows a few kilometers downstream from the Monticello gaging station, show that most of this sediment derives from upland erosion (Blair et al. 2018). Third, the model does not include an algorithm for changing channel slope, length, and sinuosity in response to changes in sediment flux (Patil et al. 2012). Again, changes in these characteristics are unlikely to be substantial over the simulation period in this study but may be important over long time scales.

9 | Conclusions

Quantifying the impacts of humans on sediment fluxes in agricultural landscapes is important to understand the extent to which farming has transformed the sediment dynamics of river and watershed systems. This study developed and implemented a coupled, semi-distributed hydrologic and sediment model to simulate water and sediment fluxes in an intensively managed agricultural watershed in the midwestern United States. Simulations estimated sediment fluxes for the modern agricultural landscape and for the native-prairie landscape that existed prior to European settlement. Sediment supply, floodplain sedimentation, sediment delivery ratio, and suspended sediment load for the two scenarios were compared across multiple scales. Results demonstrate that the transformation of the landscape from widespread prairie and scattered forest to intensive agricultural land use has led to dramatic increases in upland erosion and river suspended sediment loads, supporting the argument that intensively managed landscapes have passed a threshold and have shifted from a transformation-dominated system, in which sediment delivery to stream systems was limited by dense vegetation cover, to a transport-dominated system, in which exposed soil is readily mobilized and redistributed throughout stream networks (Kumar et al. 2018, 2023). A caveat is that the results also show that the 11-fold increase in sediment delivery to the river system and the eight-fold increase in sediment load has been accompanied by a nearly seven-fold increase in floodplain storage. Thus, the overall balance among delivery, transport, and storage has changed less than the magnitudes of sediment fluxes. Because the coupled model is capable of accurately estimating sediment load and predicting the responses of sediment load to future changes in land management practices and the impact of climate change, it provides a tool to examine how land and river management practices aimed at sediment management might influence watershed-scale sediment fluxes.

Acknowledgments

This work was partially supported by the NSF Grant #EAR-1331906 for the Critical Zone Observatory for Intensively Managed Landscapes (IML-CZO), a multi-institutional collaborative effort. We thank Dr. Murugesu Sivapalan at the University of Illinois for guidance in model design, HongYi Li at Montana State University for assistance with modeling, and two anonymous reviewers for helpful suggestions on the paper.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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